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ARE ELECTRIC VEHICLES SAFER THAN COMBUSTION ENGINE VEHICLES?

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INTRODUCTION

Replacing conventional vehicles using internal combustion engines with electrified vehicles (EV) is a challenge in many respects. Introduction of new technical solutions, especially those produced for a mass market, may substantially change and possibly increase the risks associated with the products. On the other hand, electric vehicles have other clear advantages concerning safety as they do not carry conventional fuels onboard such as petrol or diesel, both of which are flammable and toxic. Without a combustion engine onboard, the risks of fire and explosion are thus minimized. Therefore, the introduction of electric vehicles promises a transition to a clean, non-polluting, healthy and safe means of transportation (see also Chapter 6 on life cycle environmental impact).

While there is a potential for electric vehicles to be safer than conventional ones we still need to consider what other risks this technological transition will bring as the risks associated with conventional vehicles are well known to most people and thus easily dealt with in daily life. What risks are associated with a large onboard chemical energy storage? Will the hazardous traction voltage of the electrical

system pose a danger to the passengers or to rescue personnel in case of an accident? How can eventual risks be diminished in traffic, when vehicles are parked and maintained? All these aspects and more need to be considered when designing the vehicle.

Safety issues for electric vehicles considered here include mainly battery powered vehicles, vehicles which have the battery as the only means to store energy (BEVs) or range extended vehicles where the battery is still the main source of energy but an extended range can be obtained using a combustion engine, for example plug-in hybrid vehicles (PHEVs). Another type of electric vehicle is the fuel cell powered car, using hydrogen gas as fuel. In this case, safety aspects mainly concern the safe handling and storage of hydrogen. While EVs are on the market in rapidly increasing numbers today, the fuel cell car has not reached true commercial introduction yet. Compared to conventional fuels hydrogen has both advantages and disadvantages, but again the risks are different to those we are familiar with and other safety practices are needed. We will, however, not include fuel cell safety issues in this chapter.

Lithium-ion (Li-ion) batteries have high energy and power densities that make it possible to build BEVs and PHEVs with acceptable electric driving range with zero tail pipe emissions. This type of battery has therefore become the preferred choice for manufacturers of these types of vehicles. In this chapter we focus primarily on the lithium-ion battery while other battery types are discussed more briefly. Other technologies for energy storage, e.g. flywheels, compressed air and supercapacitors might be used in future electric vehicles. Presently, they are used to a very limited extent and are therefore not included.

BATTERY SYSTEM DESCRIPTION

The traction battery system in an electric vehicle consists of many parts. Figure 4.1 shows the principle layout for a traction battery system. The basic building block in the battery pack is the battery cells. The cells are connected in series in order to increase the voltage. Cells can also be connected in parallel, in order to increase capacity. Typically a battery pack for an electric vehicle consists of 100-400 cells.

A number of cells form a module, which is typically kept under 60V at present (2013) and is thus not a particular electrical hazard. A battery pack usually consists of several such modules. To monitor and control cells, modules and pack each battery system has a master Battery Management System (BMS), often in combination with one or several slave management systems (e.g. one per module). The BMS has a number of functions essential for safe operation of the battery system: (i) Parameters such as cell voltage, current and temperature are monitored in order to ensure that the battery operates within the allowed limits, (ii) balancing of cells is performed in order to keep all cells on the same level regarding state of charge (SOC), (iii) contactors placed inside the battery pack in order to connect and disconnect the battery to the rest of the vehicle are controlled, (iv) the status of the electrical insulation of the traction voltage system is monitored and (v) the BMS communicates with the other parts of the vehicle as well as supplies information to the driver. As an independent means of electrical safety the battery often

has one or several fuses, for short-circuit protection. Furthermore, the thermal management system of the battery could both heat and cool the cells in order to maintain a temperature within an efficient and safe temperature range. A mechanical housing, the battery box, is used to enclose and protect the battery pack. It has several functions and a suitable tightness-class.

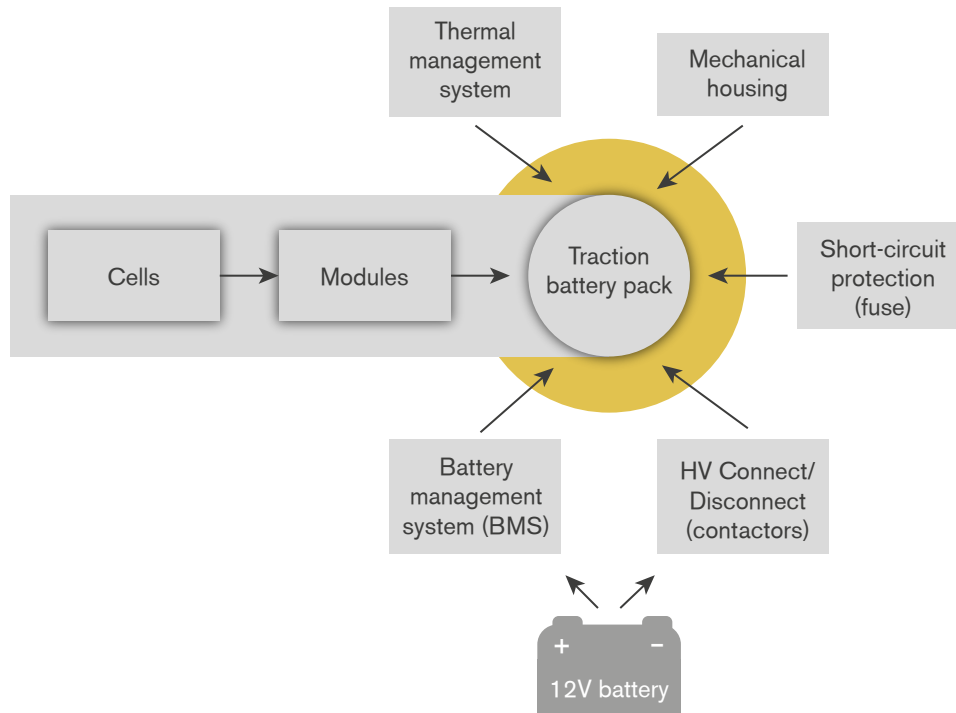


Figure 4.1 The traction battery system overview.

Typically the battery pack uses an external 12V supply from the vehicle's 12V-battery, e.g. a conventional lead-acid battery. The 12V supply is used to power up the BMS and to close the contactors. In principle, the battery could supply its own 12V by an internal DC/DC converter but an external supply is a simple solution that is commonly used.

BATTERY TYPES

Lead-acid batteries (PbA) have been used for more than 150 years and are still produced in large quantities as 12 V and 24 V vehicle batteries. There are several types, e.g. free ventilated or recombination cells (e.g. AGM, GEL). Compared to Nickel-metal-hydride and Li-ion batteries, they have lower power and energy densities and a significantly shorter cycle lifetime. Lead-acid batteries also require a long charging time, typically 10 hours. Since this should be seen as a fully mature technology it has been cost optimized. Due to its high weight and large volume it is not a real option for PHEVs or EVs, even though it was used experimentally in EVs during the 1990s. Presently lead-acid batteries are considered only for micro-hybrid electric vehicles (start and stop techniques). The safety concerns are small and related mainly to the risk of hydrogen gas production during operation. Hydrogen gas can potentially ignite and explode but the buoyancy of hydrogen gas makes it relatively easy to ventilate the battery in order to avoid the formation of

an ignitable mixture with air. Since lead acid batteries is a mature technology the battery design is very well developed to avoid these problems.

Nickel-metal-hydride batteries (NiMH) are presently dominating the HEV-market; they are used in the Toyota Prius for instance. NiMH offers significantly improved energy and power densities compared to lead-acid batteries. Further, it offers a high cycle life time and safety concerns are small. They do not, however, have the same energy storage capacity as Li-ion batteries.

Lithium-ion is the dominant battery technology today for PHEVs and EVs due to its high energy and power densities, combined with a long life time. The safety concerns are however larger than for NiMH and lead-acid batteries. This is basically due to the chemistries used for these cells but the large size of the battery systems needed for these types of vehicles also makes the consequences of a malfunction potentially more serious. We will therefore devote most of this chapter to describe safety aspects of Li-ion batteries.

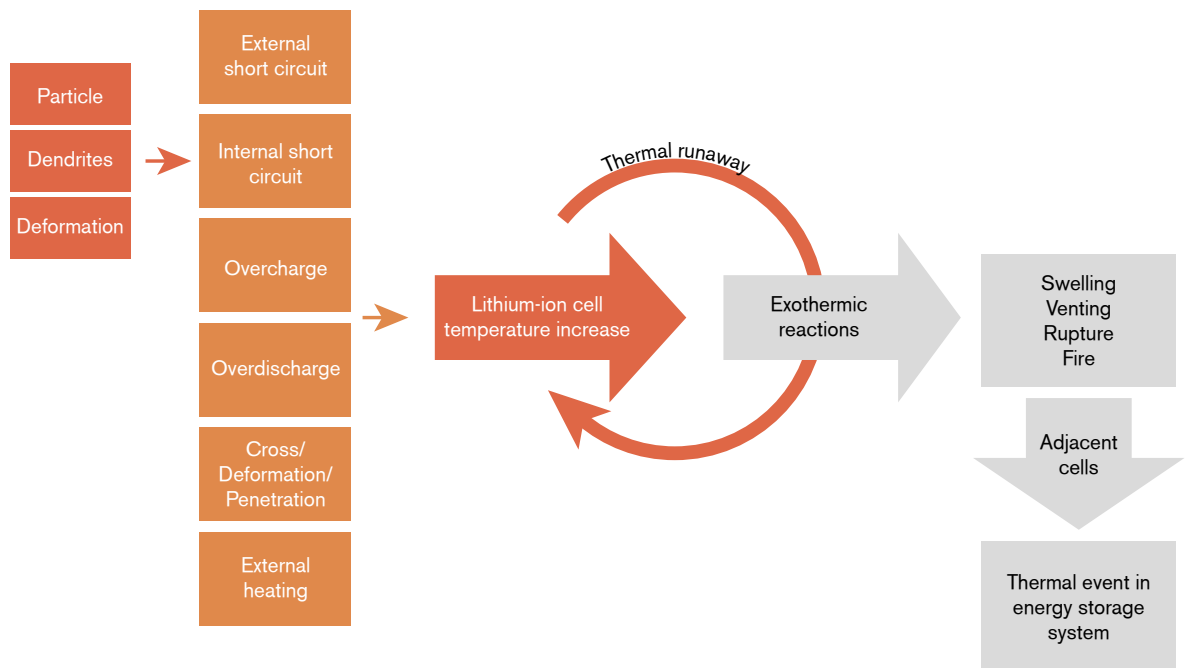
A lithium-ion cell consists essentially of anode, electrolyte, separator and cathode. The lithium ion is shuttled back and forth between the anode and cathode through the electrolyte. Even though a large number of different lithium-ion chemistries are possible there are today (2013) only a few lithium-ion chemistries that are used commercially. The anode and cathode are intercalated lithium compounds. Typically the anode is based on graphite, lithium titanate oxide (LTO) can also be used. The cathode is composed of lithium cobalt oxide (the most common type for small consumer cells), mixed oxides (manganese, nickel, cobalt, and aluminum) or phosphates (mainly iron-phosphate). The electrolyte typically consists of organic solvents, lithium salt and additives. The exact composition differs between the manufacturers and is usually a commercial secret, especially regarding the additives. The separator is a porous polymer where the pores are filled with the electrolyte; its primary function is to avoid direct contact between anode and cathode. In some cases the separator may also have the function of shutting down the ion transport in case of overheating.

The risks involved with the use of lithium-ion batteries are closely related to the chemistries used, the design of cell and system, the handling of the battery when in use and the quality of the production. The choice of cell chemistry is, in turn, determined by the demands regarding energy and power density, cost and safety for the specific application. Small size lithium-ion batteries have been used for more than a decade in consumer products, such as laptop computers and mobile phones. During this time, battery fire incidents have been reported in laptops, iPods, cargo planes and electric vehicles.¹ However, the conditions and requirements for lithium-ion batteries in automotive applications are different and more demanding than those for consumer electronics. Lithium-ion cells for the automotive industry are, for example, characterized by increased quality, safety and life time compared to that of small consumer cells, and generally use more advanced materials with higher degree of purity.

¹ Wang, Q., Ping, P., Zhao, X., Chu, G., Sun, J., and Chen, C., "Thermal runaway caused fire and explosion of lithium ion battery", *Journal of Power Sources*, 208 (2012) 210-214.

Lithium-ion batteries have many advantages but the window of stability is relatively small (both regarding temperature and voltage). The cells must therefore be monitored and controlled by the BMS. Overheating may cause a severe malfunction; if the temperature exceeds typically 120-150 °C, exothermic reactions within the cell can start. The exothermic reactions will increase the temperature further, which can trigger additional exothermic reactions. If the overall cell reaction creates a rapid temperature increase, it could result in a so called thermal runaway. A thermal runaway consists usually of one or a combination of the following events: rapid gas release, electrolyte leakage, fire, rapid disassembling/explosion.

The reason for the initial overheating may be an external short-circuit, overcharge, over-discharge, deformation of the battery by external forces, external heating or an internal short-circuit. The latter may be caused by dendrite growth, unwanted particles in the cell etc. If the overheating spreads to adjacent cells a large part of the battery system may be affected. Figure 4.2 shows how a thermal event on the cell level could develop to the system level. In order to obtain a high level of safety such a chain of events must be hindered.



Figur 4.2 Potential chain of events for a thermal event on the cell level developing to system level.

The outcome of these reactions varies with cell design and chemistry, particularly with the electrode and electrolyte composition. The combination of reactive materials and flammable components in the cell pose a risk, the electrolyte is flammable and the oxide materials may release oxygen at elevated temperatures, thus both fuel and oxidant needed for a fire might be present inside the cell.

In order to meet the demand of the automotive industry, improved battery materials have been produced. The selection of the active electrode materials (anode and cathode) strongly affects the thermal runaway and its onset temperature. Lithium iron phosphate (LFP) is for example a more stable cathode material than the

cobalt-based lithium oxides that are commonly used in consumer Li-ion batteries. Other electrode materials, for example mixed oxides with cobalt in combination with other metals (e.g. Ni, Mn, Al), have been developed in order to improve safety and other aspects (e.g. life time, cost, energy and power densities).²

The electrolyte composition and its additives, e.g. flame retardants, redox shuttles and gas release controllers, are also very important for the overall safety of the battery. The organic solvents involved, e.g. ethylene carbonate (EC) and dimethyl carbonate (DMC) are volatile and flammable. The mechanical packaging, cylindrical, soft or hard prismatic can or pouch-prismatic, also affects the cell behavior during a thermal event. For example, a cylindrical can cell could build up a much higher pressure than a pouch cell.

There are both pros and cons associated with each type of cell packaging. For example, with a cylindrical cell it can be easier to control the venting direction but higher internal cell pressure build up can be potentially more dangerous. Thus, there are a number of safety mechanisms that can be included into a lithium-ion cell construction by its manufacturer depending both on the chemistry and physical design of the battery.

It takes a long time to develop new battery technologies, typically more than 20 years. Potential future battery storage technologies is a very active field of research and one of the most interesting future battery technologies is the *lithium-air battery*, which has a huge potential compared to Li-ion batteries, e.g. the energy density is projected to be more than 10 times that of Li-ion batteries. There are, however, several challenges to be solved for the lithium-air technology, e.g. regarding life time and safety. One safety concern is how to prevent air from reaching the free lithium-metal. Li-air batteries are, however, not likely to be commercialized within at least 20-30 years.³

VOLTAGES, CURRENTS AND ELECTRICAL HAZARDS

An electrified vehicle still contains electrical energy in the battery when it is shut-down and parked. The manufacturer has constructed the vehicle in such a way that the hazardous traction voltage is kept inside the battery pack and insulated from the rest of the vehicle. In other words, all parts except the inside of the battery system can be considered as voltage free (provided there are no electrical insulation failures). It is important to understand that also an “empty” battery, meaning fully discharged, 0% SOC, still has a considerable voltage. For an electric vehicle this is still to be considered as a hazardous voltage. The definition of hazardous voltage is that it is potentially dangerous for humans, and it is usually stated as > 60 VDC (although this limit varies in different countries).

Vehicles with internal combustion engines have had a remarkable increase in vehicle safety during the last 10-20 years. Active safety is now starting to be introduced in some cars, e.g. lane departure warnings. The passive safety, e.g.

² Wang, Y., Jiang, J., Dahn, J., “The reactivity of delithiated $\text{Li}(\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3})\text{O}_2$, $\text{Li}(\text{Ni}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05})\text{O}_2$ or LiCoO_2 with non-aqueous electrolyte”, *Electrochemistry Communications*, 9 (2007) 2534-2540.

³ G. Girishkumar, B. McCloskey, AC Luntz, S. Swanson, W. Wilcke “Lithium- air battery: Promise and challenges” *Journal of Physical Chemistry Letters* 2010, Vol. 1(14), p. 2193–2203.

crash protection, has evolved greatly over the years with e.g. the NCAP testing. Computer simulations and crash tests have fostered the development of crash deformation structures significantly and increased crash and collision protection.

Electrified vehicles are likely to have the same level of passive and active safety as conventional vehicles. In order to ensure this, the safety techniques must be adapted for this new technology, e.g. during a crash, crash detection sensors inside the vehicle, also used for activation of airbags, can disconnect the traction voltage from the battery before the crash is complete. This means, that even if the electrical insulation of the traction voltage, containing the hazardous voltage, would be damaged, this voltage will be turned off. Of course, in severe crashes, there is always a risk that this might not be the case.

Presently (2013), car manufacturers crash protect the battery pack so that no short-circuit may occur in its electronics and that no lithium-ion cell can be deformed during pre-defined crash scenarios. In principle, this is done by putting the battery inside a crash protected box. This adds weight, volume and costs. In the future, it is likely that the battery pack instead becomes a part of the crash structure. Battery packs of today can handle some small deformation; this is a matter of design, which today varies depending on cell chemistry, cell design and packaging. In the future, it is likely to have safer lithium-ion cells and battery systems which could to a higher level stand a deformation. In that case the battery can to a larger extent be used in the vehicle's crash structure. The deformation protection design criteria are given by load-cases. This means that for a severe crash, which is outside the design criteria, a deformation which is larger than expected can occur. It is unrealistic and just not possible to design the crash protection for all types of extreme collisions.

The electrical drive train is made safe by several means. In general the battery cells presently used are in general very safe since judicious choice of Li-ion technology ensures that an unsafe lithium-ion cell would not be chosen. The voltage of each lithium-ion cell is in general monitored and balanced with respect to the other cells. This requires quite advanced electronics and electro-components such as fuses and contactors are used in the battery pack. The electronic parts (electrical components, processors, circuit-boards etc.) of the battery pack are similar to the parts used in conventional vehicles by a large part of the industry. In case of errors in the electronics or sensor failures an unsafe situation could occur. However, the manufacturers work with functional safety (e.g. ISO26262) in order to minimize these risks.

The battery safety is ensured by the manufacturer by adding layer by layer of safety, schematically shown in Figure 4.3. Deformation of the battery cell can result in a thermal event. Therefore the battery is usually placed outside the deformation zone. For a passenger car, this generally results in a battery placement inside or beneath the passenger compartment.

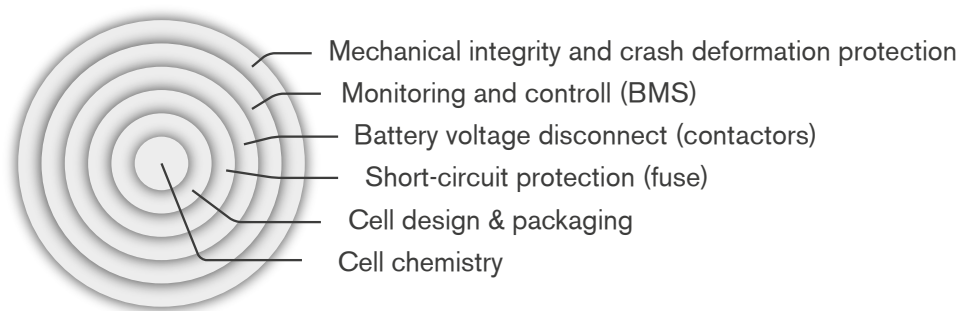


Figure 4.3 An example of battery safety layer by layer.

The components and traction voltage cables carrying a high voltage are usually very well insulated and protected. The risk that a human, e.g. driver, passenger, rescue personnel or firefighter, would be exposed to an electrical shock is in general very low. The traction battery has a so called floating ground, meaning that there is no electrical connection between the traction battery poles and the vehicle chassis ground. The 12V/24V vehicle battery on the other hand (for both conventional ICE vehicles and EVs) uses the vehicle chassis ground as the current return path to the negative 12V/24V pole. The principle of the floating ground and the current path of the traction battery are shown in Figure 4.4.

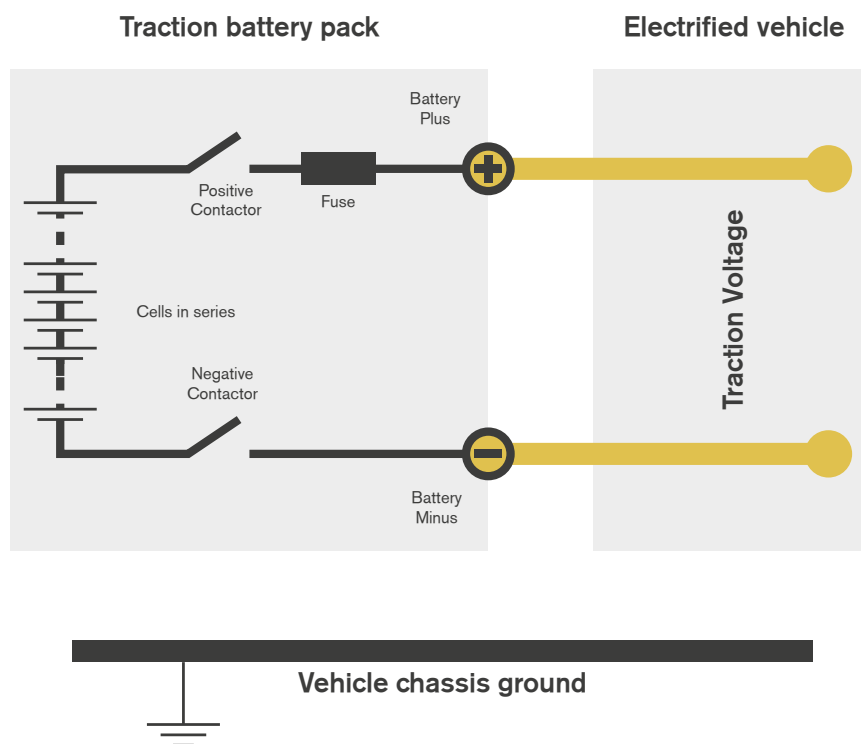


Figure 4.4 Traction battery pack current path and the floating ground principle. If there are no insulation fault(s), there are no electrical connections between vehicle chassis ground and the battery poles.

Both DC (direct current) and AC (alternating current) voltages are present in EVs (see also Chapter 3). The DC voltage comes from the traction battery and the AC voltage is used by the power electronics and electric motor. Both pose a danger for humans in case of an electric shock caused by either a direct touch of the battery poles, or indirectly by touching the metal chassis. In order for such exposure

to occur, two insulation faults are required (one at each pole of the battery) and the victim must touch metallic parts with the different potentials at the same time. Figure 4.5 shows the principle of a double insulation fault.

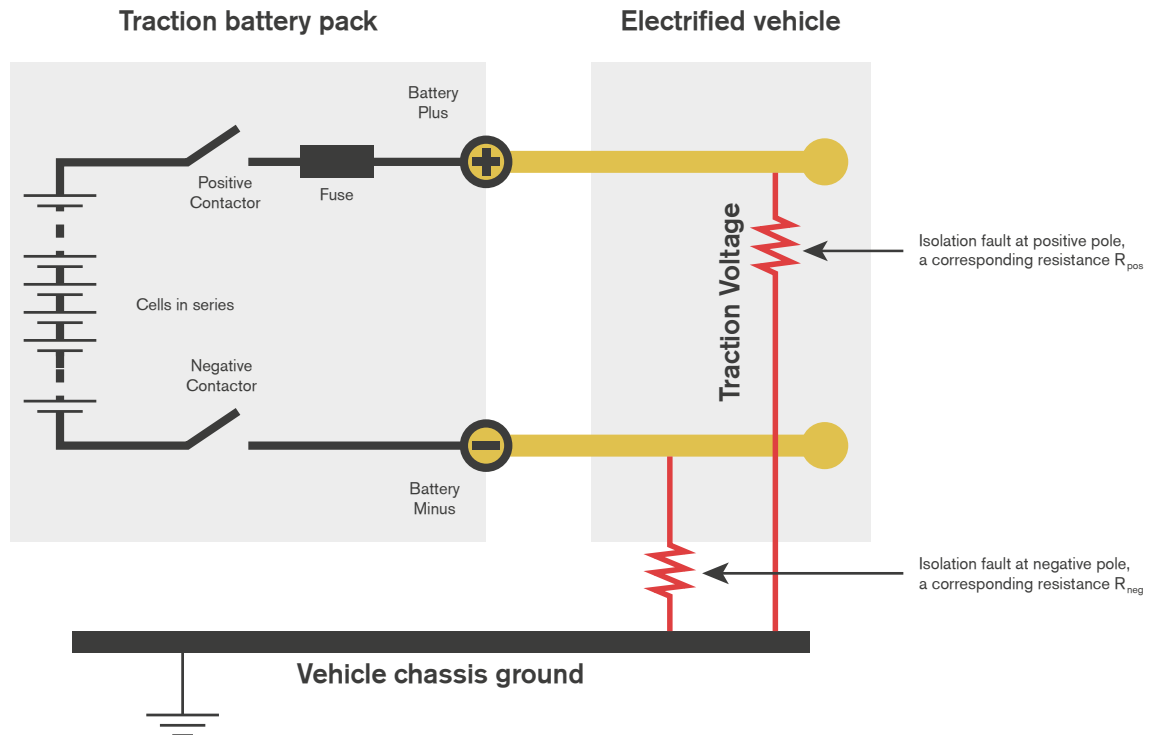


Figure 4.5 Principle figure that shows a double insulation fault. This means one insulation fault at the plus and one at the minus pole. They are shown as two resistances, R_{pos} and R_{neg} , connected to ground. This creates a current path between battery plus and battery minus.

The vehicle chassis ground is usually constructed to electrically act as one pole of the 12/24 V system by having most metal parts connected to each other. In the situation of a double insulation fault there will be a short-circuit through the chassis. Since the current takes the easiest path (i.e., the conducting path with the lowest resistance), the human body will hardly be affected by touching the chassis ground. On the other hand, there could be a potential risk for service personnel repairing a damaged electric vehicle, since they can, during disassembly, have two chassis ground, one with the negative battery potential (minus) and the other with positive battery potential (plus). There are however, protection means for this, e.g. insulation measurements, electrically insulated gloves (typically marked for safe use up to 1000V), and knowledgeable maintenance staff should be able to minimize this risk.

It could be mentioned that hazardous voltages, both DC and AC, inside the components in an EV, sometimes are referred to as “high voltage”. From the automakers perspective, this term conveniently separates the 12/24V system (“low voltage”) and the 300-600 V system (“high voltage”) for the electric drivetrain and the traction battery. However, to name the hazardous traction voltage as “high voltage” is somewhat misleading since there is already a definition and a long time tradition to use the term “high voltage” within the mains (electricity grid), for voltages over 1000 VAC or over 1500 VDC. The term “HV” is actually in automotive industry sometimes interpreted as “hazardous voltage” (instead of “high voltage”).

FIRES, GASES AND EMISSIONS

The energy stored in the battery in an electric vehicle is essentially released once you connect the two poles while the energy in a conventional vehicle requires the fuel to be mixed with air at the right proportion and pressure and then the gas mixture needs to be ignited by a spark or by exposure to high temperatures; the spark could for example be created by the starter engine. The higher voltages and currents used in an electric vehicle may be a risk for fires and lithium-ion batteries pose a special risk as the electrolyte is combustible, with properties similar to gasoline or LPG. Furthermore, the battery might progress into thermal runaway as described previously. One of the safety mechanisms used in these cells to prevent a more severe incident to occur is venting. The gases released in a venting situation are, however, highly toxic and flammable. In particular, a venting cell would release hydrogen fluoride (HF) which is highly toxic. Venting would also release many other fluorinated substances that have a potential of being toxic, but the toxicity of these has not yet been publically investigated.

If a fire starts, many of these substances might be consumed in the fire but the knowledge in this field is still limited and more research is needed regarding evolved gases from battery fires. HF is a gas that evolves in many different types of fires. Recently INERIS in France set two different electric vehicles and two similar conventional ICE vehicles on fire and measured the heat release rate during the fire and also gases evolved including HF. They found that the heat release rate was of the same order of magnitude, independent of vehicle type. High concentrations of HF were emitted in the beginning of the fire for all four vehicles. This might have been caused by the air-conditioning system. Some HF also evolved later in the fire for EVs, but the concentration was less than that of the first spike of HF and distributed over a longer time period.⁴

Anecdotal evidence exists that electric vehicles burn fiercely and that the fire is difficult to extinguish. The INERIS experiment does not confirm this burning behavior but the fire was started by a gas burner in one of the seats in these experiments. Other means of starting the fire might give another result but there are at present a very limited number of investigations, if any, available on this topic.

Extinguishment of a fire is an area where there still are questions to be answered. The advice from manufacturers is often to let the vehicle burn or to use water or sand. Letting the vehicle burn is not a viable option in e.g. a garage, a ferry or in a tunnel. Research for fire-fighters has until now mainly focused on extrication of people from crashed cars and not on extinguishment. In general, water is an excellent extinguishing medium that has a very high extinguishing power per mass. However, when it comes to potential live electric parts the advice is often to avoid using water. Research is therefore needed on how to attack a fire in a battery. Would it be safe to use water both in terms of the risk of electric shock and when it comes to gases evolved? Should other methods be used to respond to a fire? In addition a fire in the battery system might be difficult to reach. It is only just recently that a first extinguishing study was available. This study was conducted by

⁴ A. Lecocq, M. Bertana, B. Truchot and G. Marlair "Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle" Proceedings of FIVE 2012, Chicago, 27-28 September 2012

DEKRA in Germany where batteries were extinguished using water and different additives.⁵ They conclude that more water was needed for the EV fires than for vehicles with conventional internal combustion engines.

The EV users would like to be able to charge their vehicle fast in some situations, similar to filling fuel into a conventional vehicle, or at least have a significantly shorter charging time than that of overnight charging. Systems for fast charging are therefore under development. Fast charging requires high currents and one would therefore intuitively associate this with larger fire risks. The high current would result in a higher risk of overheating or other malfunctions in the charging station or in the vehicle itself and thus careful design is important. These risks are well known and when the number of fast charging stations will grow actions will be taken to minimize associated risks.

INCIDENTS

Despite the manufacturers efforts to produce safe batteries some events have occurred that have reached media attention. One of the major media events in June 2011 was the fire that started in a GM Chevrolet Volt car three weeks after a crash test. The incident was thoroughly investigated by NHTSA and the chain of events was reproduced. The reason was found to be that the cooling media had leaked over the battery and then dried; leaving crystals that finally short-circuited the battery through the metallic belt around it. Changes have since been made to the design, e.g. to avoid leakage of cooling media.

Another event that has drawn some media attention is the fires that occurred after hurricane Sandy hit the Atlantic coast in the New York area in November 2012. At the harbor of Newark, New Jersey, thousands of parked vehicles were flooded. The cars were brand new shipped in from abroad. The water wave that followed Sandy immersed the parked vehicles in 1.5-2.5 meters of seawater during several hours. It has been reported that sixteen Fisker Karma PHEVs and a few Toyota Prius HEV and PHEV burned. Unconfirmed statements from Fisker and Toyota blame the fires on short-circuits in the 12V vehicle electronics. NHTSA and Fisker have started an investigation to find the cause of the fires. To be submersed in 1.5-2.5 meter deep seawater for several hours is a very severe test for an electrical system in general which can only be met with IP68 class or equal water-tightness level. Seawater is a good electrical conductor and can cause short-circuits, for both low voltage (e.g. 12/24V vehicle voltage) systems and for the traction voltage in electrified vehicles.

Apart from these events there are some other events that have not reached media interest. Focus on battery safety has to a large extent been on the cells as such and much progress has been made in this respect. The traction voltage parts of the system are also subject to many protection steps in many cases. It is important, however, to take into account that the cells are part of a large system with a lot of electronics that needs to be functioning in a harsh environment as vehicles are subject to many different situations.

⁵ Electric car batteries 'at least as safe as combustion cars' (2012)

OUTLOOKS FOR THE FUTURE

Safety issues are of major concern in any introduction of a new product into the market as negative publicity might have a negative impact of general public's perception of a product and the products potential to succeed. Key aspects here are to design safe products and be very open about events that have occurred as ample correct information is the best way to avoid rumors. One threat to a safe introduction could be home-converted vehicles as these, with their limited budget, would have difficulties reaching the same high safety levels as commercially built vehicles.

Lithium-ion batteries for automotive use have shown an increased safety regarding fire and explosion through e.g. improved electrode and electrolyte materials. Therefore, the focus of lithium-ion safety research has moved increasingly towards the safety aspects associated with released gases and smoke, as well as other electrical aspects.

The choice of material for future batteries is a fundamental issue including possible scarcity problems. Further, the choice of different additives to obtain sufficient safety, e.g. flame retardants, or other necessary battery characteristics can result in life-cycle issues which will be untenable. New technologies are necessary which will no doubt pose new risks which will need to be addressed.

The number of EVs on the road is still low so reliable statistical studies of incidents and accidents are not possible yet, anyhow, the numbers are increasing steadily and with that also the possibility to conduct different safety studies as the price per vehicle is lowered and the vehicles are commercially available and not only leased etc. It is therefore likely that we will see an increasing number of studies on different safety aspects that still need to be resolved which will foster the development of safer EVs.